Grass Barriers for Reduced Concentrated Flow Induced Soil and Nutrient Loss

Humberto Blanco-Canqui,* C. J. Gantzer, S. H. Anderson, and E. E. Alberts

ABSTRACT

Vegetative filter strips (FS) perform poorly for reducing losses of sediment and nutrients in concentrated flow. Stiff-stemmed grass barriers (B-FS) above the FS may be a companion treatment to improve the FS performance. This study evaluated the effectiveness of warm-season switchgrass (*Panicum virgatum* L.) barriers planted above fescue (*Festuca arundinacea* Schreb.) FS in reducing runoff water, sediment, N, and P losses in concentrated flow from an Aeric Vertic Epiaqualf on a 5% slope. Simulated rainfall was applied on plots consisting of a 1.5-m-wide by 8-m-long pollutant source area with an artificially constructed channel to concentrate surface runoff. The source area was bounded downslope by either an 8-m long fescue FS or 0.7 m of active or dormant barrier above a 7.3-m-long fescue FS. The B-FS treatment also reduced sediment loss by 91% while the FS reduced sediment by only 72% ($P < 0.01$). The B-FS also reduced sediment loss by 90%, whereas FS reduced sediment only 60% when inflow was added to the plots. The B-FS trapped 4.9 times more organic N, 2.3 times more NH_4–N, and 3.7 times more particulate P than FS at 0.7 m ($P < 0.01$). Sediment and nutrient trapping increased significantly with FS length. Switchgrass barriers above the FS dispersed and temporarily ponded concentrated runoff, enabling increased sediment deposition. Barriers may be a potential conservation strategy for rehabilitation of lands affected with concentrated flow where traditional practices are inadequate.

Grass barriers are narrow strips (<1.2 m) of stiff-stemmed tall grass planted for controlling soil erosion. Barriers differ from FS in that FS are wider areas of vegetation (>5 m) established between agricultural fields and streams for reducing transport of nonpoint-source (NPS) pollutants in runoff. While FS are well studied and often used as part of conservation systems, research on barriers for controlling erosion is limited (Eghball et al., 2000; Gilley et al., 2000). Filter strips are effective in reducing sediment and nutrient loss in runoff (Daniels and Gilliam, 1996; Schmitt et al., 1999; Abu-Zreig et al., 2003); however, their effectiveness for concentrated flow is questionable (Dabney et al., 1995; Dosskey et al., 2002). In fact, Dillaha et al. (1989) recommended that FS should not be used in concentrated flow areas. Concentrated flow erosion in farmlands is a common problem. Field topography often causes runoff to concentrate in natural swales as runoff moves downslope. Erosion occurring in these channels is known as concentrated flow or ephemeral rill erosion because it continues to erode in the same locations across years. Although ephemeral rills can be smoothed over by tillage, their contribution to soil erosion may account for >30% of total erosion (Spomer and Hjelmfelt, 1986).

Grass barriers may be an effective companion treatment to FS for controlling concentrated flow of surface runoff because barriers have stiff stems that remain erect, providing greater hydraulic resistance to runoff than FS (Dunn and Dabney, 1996). Effectiveness of barriers for controlling losses of sediment and nutrients in concentrated flow has not been studied (Dabney et al., 1995). Barriers may be an economical and ecological alternative to expensive terraces to control erosion. Studies on the effectiveness of grass barriers when used in conjunction with FS for reducing concentrated flow in field plots are limited (Dosskey et al., 2002).

Many have assessed the length effect of FS on reducing sediment and nutrients in sheet runoff (Chaubey et al., 1994; Srivastava et al., 1996), but few data exist on the effectiveness of FS on reducing concentrated flow in relation to FS length. Knowledge of length effect of FS on sediment and nutrient removal is essential toward designing FS for controlling transport of pollutants. Land taken out of production for FS establishment may be reduced if barriers are added to FS to improve its effectiveness.

Research on the effectiveness of grass barriers for controlling concentrated flow from varying sizes of pollutant source area is also needed for developing management guidelines. Information about the effectiveness of active and dormant grass B-FS for controlling sediment and nutrient losses is scanty. Barriers may have reduced performance on erosion reduction in spring when runoff and soil losses are generally high and barriers are dormant (Tischler et al., 1994; Ghidey and Alberts, 1998). Our hypotheses are (i) grass barriers, when used in conjunction with FS, can improve significantly the FS performance, thus reducing the land taken out of production for FS establishment, and (ii) dormant grass barriers are as effective as active barriers for reducing sediment and nutrients in runoff. If this is true, grass barriers may be added to FS design to improve performance.

The objectives of this study were to (i) determine if active and dormant switchgrass barriers planted above fescue FS increased sediment, N, and P trapping efficiency in concentrated flow, and (ii) investigate the influence of FS length with and without barriers on the reduction of sediment and nutrient loss in concentrated flow. The study evaluates the effectiveness of barriers and FS for reducing concentrated flow in field plots where no barrier failure occurred during testing.

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Abbreviations: ANCOVA, analysis of covariance; B-FS, barrier(s) above a fescue filter strip; FS, filter strip(s); NPS, nonpoint-source.

MATERIALS AND METHODS

Study Description

The study was conducted at the Bradford Research and Extension Center located 17 km east of Columbia, MO. A site of 23 by 85 m was selected. The soil was a moderately eroded Mexico silt loam (fine, smectitic, mesic Aeric Vertic Epiaqualfs) maintained in an established stand of perennial fescue grass (>10 yr). The site has a depth to argillic horizon of 85 ± 5.8 mm and a slope of 4.9 ± 0.6%.

Eighteen 1.5- by 16-m plots with six treatments replicated three times were arranged in a randomized complete block design (Fig. 1). The six treatments were (i) a fescue FS, (ii) a switchgrass barrier above a native species FS, (iii) concentrated flow above a fescue FS with no barrier (FS), (iv) concentrated flow above a barrier plus fescue FS (B-FS), (v) a switchgrass barrier above a fescue FS, and (vi) a check managed in continuous cultivated fallow without switchgrass barrier or FS. On the basis of the objectives of our study, the treatments evaluated in this paper were only FS and B-FS (Fig. 2). To gain additional degrees of freedom for testing the differences among the treatments, data from the six treatments were used to calculate statistics.

The long dimension (16 m) of the plots was oriented up- and down-slope, and soil berms 200 mm in height and 250 mm at their base were constructed as plot borders. Berms were treated with anionic polyacrylamide at a rate of 9 kg ha^{-1}, and covered with a Du Pont nonwoven geotextile fabric to reduce berm erosion to nondetectable levels. Plots were designed with an upslope 1.5- by 8-m pollutant source area managed under continuous cultivated fallow, above a downslope FS area of the same size. A 3-m-wide alley was included between plots to facilitate positioning a rainfall simulator (Fig. 1). Glyphosate herbicide (*N*-phosphonomethyl-glycine) was applied at 8 L ha^{-1} to kill existing vegetation in the pollutant source area in June 2001. The source area was tilled with a hand rototiller to

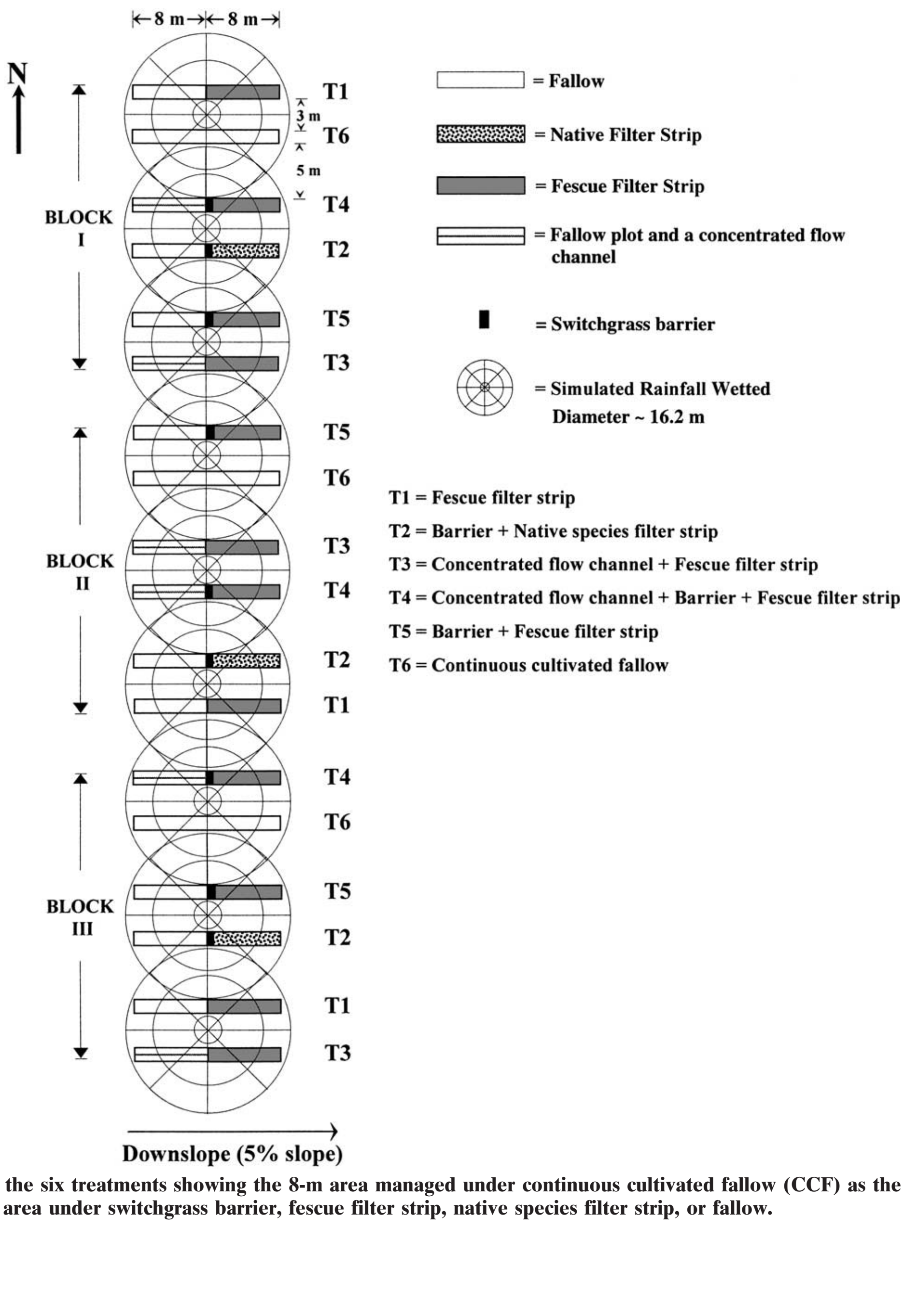

Fig. 1. Plot layout of the six treatments showing the 8-m area managed under continuous cultivated fallow (CCF) as the sediment source area above an 8-m test area under switchgrass barrier, fescue filter strip, native species filter strip, or fallow.

a depth of ≈80 mm in July 2001 and managed under continuous cultivated fallow by rototilling after rainfall events. A 0.7-m switchgrass barrier was established at the downslope edge of the pollutant source area just above the FS. Barriers were established by transplanting mature switchgrass plants in July 2001. Existing fescue was used as FS in both treatments. The FS areas were managed under fescue and mowed to a height of ≈100 mm periodically. In this paper, the word *barrier* will be used to signify a switchgrass barrier.

A V-shaped channel, 200 mm wide by 100 mm deep, was constructed in the center of the sediment source area of the two treatments to simulate concentrated flow conditions. The channel was constructed by excavating soil from the midline of the plot to the depth of tillage with a shovel immediately after tilling the sediment source area, which was done a day before rainfall simulation (*dry-run*). The channel was shaped to a V-shaped geometry.

Rainfall Simulation

Simulated rainfall was used to evaluate the B-FS and FS performance in Aug. 2002. A rotating-boom rainfall simulator was used (Swanson, 1965). The simulator was positioned between two plots to supply rainfall to a plot pair. Rainfall application was 66 ± 5 mm h^{-1}. Water from a lake nearby was used for the rainfall simulation, which had an electrical conductivity of 1.15 ± 0.10 dS m^{-1}. The simulated rainfall protocol began with a dry-run simulation for 1 h. A subsequent *wet-run* simulation was done ≈24 h later at the same intensity and duration. The dry and wet runs were designed to simulate large rainfall events when most soil erosion is likely to occur. This intensity storm has a recurrence interval of a 10-yr return period for mid-Missouri (Hershfield, 1961). The rain intensity is a severe case that might occur in mid-Missouri for 1 h in two consecutive days. Fertilizer (13% N, 13% P_2O_5, and 13% K_2O) was applied to the pollutant source area 24 h before simulation at 80 kg ha^{-1}of N, 35 kg ha^{-1} of P, and 66 kg ha^{-1} K. Fertilizer was uniformly broadcast and incorporated to ≈80 mm with a rototiller. Although no crop was grown, the fertilizer application facilitated evaluation of B-FS and FS effectiveness to reduce nutrient loss.

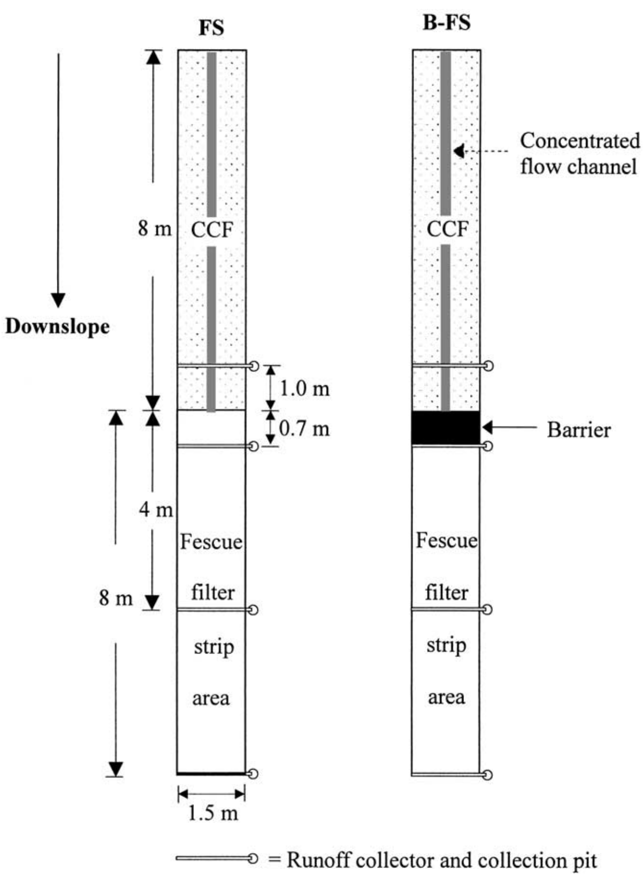

Fig. 2. Schematic of the two treatments under concentrated flow, including switchgrass above fescue filter strip (B-FS) and fescue filter strip (FS) abutted to the 8-m sediment source area managed under continuous cultivated fallow (CCF).

Runoff Collection and Sampling

Collectors having a V shape (0.08 m wide, 1.5 m long, and 0.06 m deep) were constructed of angle iron to facilitate runoff water sampling. Each collector was covered with a hinged cover fitted with a watertight gasket to close it to the trough between sampling periods. A V-shaped groove was cut in the soil to place the runoff collector. Collectors were anchored with four steel spikes (10-mm diam. by 250 mm long) to eliminate runoff passing underneath them. Collectors were set to a 3% slope to produce sufficient hydraulic head to facilitate water flow laterally into containers in collection pits. In the cover-closed position, runoff passed over the collector. The hinges allowed the collector to be quickly opened for runoff sampling and then closed. Runoff collection equipment was installed across the plot width at 1 m above the downslope edge of the pollutant source area and in the FS area at 0.7, 4, and 8 m below the pollutant source area (Fig. 2). Collection pits of 300-mm diam. by 250-mm depth were dug just outside the plot area to allow placement of sampling containers (Fig. 2).

Runoff collection was performed only during the 1-h wet runs. Runoff was sampled every 10 min. for 5 s at all sampling positions during the run. Samples were collected sequentially, first from the collector at the downslope position, and then sequentially upslope from other collectors. This allowed sampling without affecting downstream runoff (Chaubey et al., 1994; Srivastava et al., 1996). Six samples were collected from each point, producing 24 samples from each plot-event, totaling 144 samples from the 6 plots studied. There was no significant interference of grass, debris, and sediment while closing the runoff collectors supporting other studies that used similar collection system (Chaubey et al., 1994; Srivastava et al., 1996). During nonsampling times, there was no runoff from the collector running into the collection pits, thereby indicating that the collector was watertight and hence all the runoff passed over the collector. Total volume and weight of the samples were recorded. Runoff volume was regressed against time of collection, and the resulting regression equations were integrated across time from 0 to 60 min to compute runoff volume on a 1-h basis, assuming that the runoff hydrographs at all sampling positions were the same for both treatments. Runoff depth was computed by the ratio of the runoff volume to the contributing area above a sampling point. To overcome the dependence of runoff volume on the contributing area, runoff was expressed as depth as it is commonly reported in similar studies (Dillaha et al., 1989; Daniels and Gilliam, 1996; Gilley et al., 2000). Runoff ponding above the experimental treatments was measured vertically by inserting a meter stick into the pond. A total of six measurements of runoff depth were made simultaneously with the runoff sample collection.

Sediment, Nitrogen, and Phosphorus Analysis

Runoff samples were stirred to suspend sediments, and two aliquots were taken for analysis. One 0.5-L aliquot was used for determination of sediment concentration. One 0.25-L aliquot of a composite of the samples for each sampling position across time was used for N and P analysis. Samples for chemical analysis were stored in an insulated cooler and taken to the laboratory within ≈4 h of a run. Sediment concentration in runoff samples was measured by evaporation (Brankensiek et al., 1979). Samples for analysis of soluble forms of N and P were filtered through a Whatman No. 1 filter paper for determining nitrate (NO_3–N), ammonium (NH_4–N), and orthophosphate (PO_4–P) concentrations. Samples were then stored at 4°C to inhibit chemical and biological transformations until analyzed (within ≈10 d of collection). Total N and P concentrations were determined from the unfiltered portion of samples. Analysis of N and P was conducted using a Lachat flow injection analyzer (Lachat QuikChem 800 Zellweger Analytics, Milwaukee, WI). Mass of sediment and nutrients were computed as the product of runoff and concentration (Eghball et al., 2000). Organic N was calculated as the difference of NO_3–N and NH_4–N from total N, while particulate P was the difference between total P and PO_4–P (Eghball et al., 2000). Concentrations of NO_3–N (0.2 mg L^{-1} ± 0.1) and PO_4–P (0.02 mg L^{-1} ± 0.01) in the lake water supplying the simulator were very low and thus are not expected to influence the treatment differences. Sediment trapping per unit area was computed by dividing the sediment amount by the corresponding contributing area above a sampling point in accord with Dillaha et al. (1989) and Sheridan et al. (1999).

Addition of Inflow

To further assess the effectiveness of B-FS and FS for controlling concentrated flow, a second experiment was conducted in April 2003 by adding inflow to the upper edge of the pollutant source area when barriers were dormant. The work was designed to compare the B-FS and FS performance when runoff and sediment losses are generally high. Protocols of wet-run simulations and sampling were performed as previously discussed. Supplemental inflow using water from the lake was added to simulate greater runoff occurring from a larger pollutant source area. Simulated rainfall and supplemental inflow were applied simultaneously (Laflen et al., 1978; Misra et al., 1996). The simulated rainfall during the study with addition of inflow was 62.5 ± 3 mm h^{-1}, which was slightly lower than that during the study without addition of inflow (66 ± 5 mm h^{-1}).

Inflow was applied at 2.5, 5.0, 7.5, 10.0, and 12.5 L min^{-1} to simulate pollutant source areas of 1.2, 1.4, 1.6, 1.8, and 2.0 times (1.2×, 1.4×, 1.6×, 1.8×, and 2.0×) the actual plot size. The inflow rates were determined based on the amount of runoff that would occur from the 1.5- by 8-m source area under simulated rain application at 62.5 ± 3 mm h^{-1}, assuming that the infiltration rate is practically negligible when the soil is saturated. Therefore, a runoff rate of 12.5 L min^{-1} is expected to occur from the given source area receiving 62.5 ± 3 mm h^{-1} of simulated rainfall. The inflow rates were then estimated as a fraction of the total addition (12.5 L min^{-1}) by a 20% increment of the source area for each inflow addition.

Inflow was simultaneously added by pumping from a 3.7-kL polyethylene tank equipped with flow meters to regulate rates (model FP-5300, Omega Engineering, Inc., Stamford, CT). Inflow entered plots through a 1.5-m wide, 80-mm-i.d. pipe. The pipe was set at the top of the source area and had 10-mm diam. holes drilled at 50-mm intervals on the downslope side to allow uniform water delivery onto a 0.15- by 1.5-m piece of geotextile fabric to reduce scour erosion. Water was added 10 min after the start of simulated rainfall and continued throughout the experiment. Each inflow rate was applied for 15 min, after which runoff samples were collected. The inflow rate was then increased to the next higher rate, and the process was repeated. Runoff weight was measured at each sampling point, and aliquots were taken for sediment concentrations. Runoff water and sediment mass were integrated across time for a total of 15 min of simulation. Only sediment concentrations were measured in these runoff samples.

Statistics

The General Linear Models (GLM) procedure of SAS (SAS Institute, 1999) was used to test the hypotheses that runoff, sediment, and nutrient reduction differences between adjacent sampling positions (−1 and 0.7, 0.7 and 4, and 4 and 8 m) are the same. Orthogonal contrasts were used to test the main effects for B-FS and FS. Analysis of Covariance (ANCOVA) was conducted to examine the homogeneity of residual variances, regression linearity, regression slope, and slope intercepts of relative runoff, sediment, and nutrient mass vs. inflow rate and distance. Regressions were used to indicate the relationships of sediment and nutrient movement with inflow rate. The percentage values of runoff, sediment, or nutrient were computed using Eq. [1]:

$$\% = [A_i - A_l)/A_i] \times 100, \qquad [1]$$

where A_i is the amount of runoff, sediment, or nutrient collected at −1 m sampling position above the downslope end of the source area and A_l is the amount of runoff, sediment, or nutrient leaving each sampling position (0.7, 4, and 8 m).

RESULTS AND DISCUSSION

Runoff

Mean and relative mean runoff amounts from the treatments at each sampling position are shown in Table 1 and Fig. 3A, respectively. Summary of statistics is presented in Table 2. The comparison of B-FS and FS treatments between 1 m above and 0.7 below was significant ($P < 0.05$; Table 2). At the 0.7 m position, the B-FS treatment reduced runoff 16% while the FS treatment reduced runoff 13% relative to that exiting the pollutant source area. This indicates that the B-FS treatment was more effective in reducing runoff at 0.7 m. As the runoff entered the B-FS from the source area it spread out, forming backwater upslope of the B-FS. Runoff ponding above B-FS had a measured depth of 0.15 ± 0.02 m and extended 0.93 ± 0.03 m upslope of the B-FS, creating temporary water detention storage, thus increasing time for infiltration and sediment deposition (Kemper et al., 1992). As the depth of runoff ponding increased, runoff moved sparsely through the barriers at first and then spread out densely as it entered the FS area below. There was no significant runoff ponding above the FS treatment compared with B-FS treatment. The increased effectiveness of B-FS is likely because of deep rooting of switchgrass barriers (Tufekcioglu et al., 1999) and considerable runoff ponding upstream of the barriers (Dabney et al., 1995). The difference in runoff between B-FS and FS decreased with length of FS ($P < 0.01$; Fig. 3A). At the 4-m point, runoff reduced by 27% in the B-FS treatment and by 25% in the FS treatment. At 8 m, runoff decreased to 37% in the B-FS treatment and to 32% in the FS treatment. Overall, our results

Table 1. Mean ($n = 3$) surface runoff, sediment mass, and nutrient mass for fescue filter strips with barriers (B-FS) and fescue filter strips without barriers (FS) by sampling position under concentrated flow conditions.

	Treatments			
Position	B-FS	FS	Difference	SD†
m				
		Surface runoff, mm		
−1	61.1	62.8	1.70	1.22
0.7	51.1	54.8	3.6	0.62
4	45.1	46.5	1.4	1.05
8	38.8	42.0	3.2	0.94
		Sediment, Mg ha^{-1}		
−1	13.59	13.15	−0.44	0.47
0.7	0.96	3.74	2.88	0.06
4	0.39	1.23	0.85	0.05
8	0.11	0.38	0.27	0.01
		Organic N, kg ha^{-1}		
−1	5.00	4.94	−0.06	0.25
0.7	0.58	2.84	2.26	0.13
4	0.20	0.85	0.66	0.12
8	0.12	0.69	0.57	0.04
		NO_3–N, kg ha^{-1}		
−1	0.71	0.73	0.02	0.12
0.7	0.44	0.58	0.14	0.04
4	0.30	0.37	0.07	0.04
8	0.19	0.27	0.08	0.02
		NH_4–N, kg ha^{-1}		
−1	1.98	2.02	0.04	0.16
0.7	0.53	1.24	0.72	0.04
4	0.37	0.57	0.19	0.03
8	0.14	0.33	0.19	0.03
		Particulate P, kg ha^{-1}		
−1	2.28	2.31	0.04	0.16
0.7	0.29	1.08	0.78	0.07
4	0.24	0.31	0.07	0.01
8	0.13	0.18	0.05	0.01
		PO_4–P, kg ha^{-1}		
−1	0.89	0.95	0.07	0.03
0.7	0.16	0.27	0.11	0.01
4	0.10	0.16	0.07	0.01
8	0.05	0.12	0.06	0.01

† SD = Pooled standard deviation for the mean of the two treatments.

show that barriers, when added to FS, improve the FS performance on reducing concentrated runoff.

Sediment

The effectiveness of the treatments for trapping sediment was compared at 0.7 m below the source area. Both the B-FS and FS were highly effective for reducing sediment loss (Fig. 3B). The B-FS treatment reduced 91% of the sediment and the FS treatment reduced 72% of the sediment. The difference between treatments was significant ($P < 0.01$; Table 2), confirming our hypothesis that B-FS treatment is more effective than FS for trapping sediment under concentrated flow conditions. Results agree with Meyer et al. (1995) who showed that 0.2-m switchgrass barriers trapped 61% of sediments, while 0.28-m of fescue FS trapped only 46% in a flume study. Dabney et al. (1995), in a lab study, also reported that B-FS dispersed more concentrated runoff and retained two times more sediment than fescue FS.

Probable mechanisms for the greater sediment reduction in B-FS are linked with changes in flow dynamics through at least three processes. First, the B-FS may intercept concentrated flow across the channels decreasing velocity and dispersing runoff. Second, decreased velocity and increased ponding may promote deposition, forming a 0.11 ± 0.08-m-high delta. Third, ponding may absorb runoff energy that would cause soil detachment and transport, reducing the erosion and transport capacity. Meyer et al. (1995) observed that depth of ponding above switchgrass barriers was ≈0.4 m in a laboratory flume at 5% slope. Filtering was a dominant process by which the sediment was stopped in the FS treatment, as little ponding occurred.

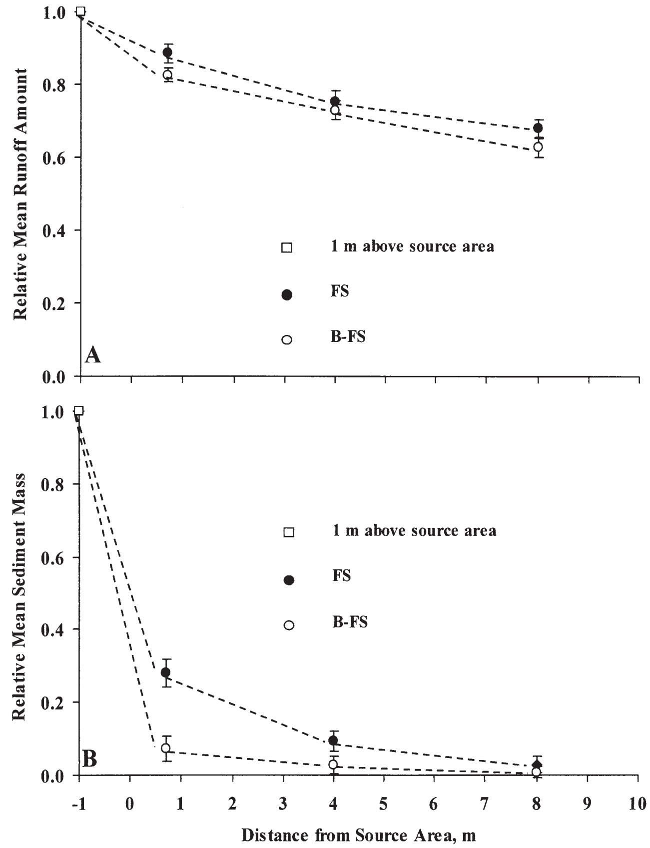

Fig. 3. Relative (A) runoff amount and (B) sediment mass by distance from source area (0.7, 4, 8 m) of fescue filter strips with barriers (B-FS) and fescue filter strips without barriers (FS). Error bars are standard errors of the mean ($n = 3$).

Sediment Transport vs. Filter Strip Length

The effect of the FS length on sediment transport is shown in Fig. 3B. Sediment decreased with distance in both treatments. Most of the sediment deposition occurred near the downslope boundary of the pollutant source area. Fig. 3B illustrates a sharp decrease of relative sediment mass between −1-m and 0.7-m sampling positions particularly in the B-FS treatment. At 0.7 m, B-FS reduced 91% and FS reduced 72% of sediment. This drastic drop of sediment transport is attributed to the runoff ponding above B-FS and filtering of sediment in the FS. The small decrease in sediment mass below 0.7 for the B-FS is due to the deposition of aggregates and coarse sediment above the B-FS. Sediment deposition above the B-FS probably left finer particles sus-

Table 2. Summary of statistical significance of differences in runoff, sediment, and nutrients for the three grass strip lengths (0.7, 4, 8 m) of fescue filter strips with barriers (B-FS) and fescue filter strips without barriers (FS).

Source	df	Runoff	Sediment	Organic N	NO_3–N	NH_4–N	Particulate P	PO_4–P
		Probability < *F*						
		Contrast positions 1 m above and 0.7 m below source area						
B-FS vs. FS	1	0.03*	0.01**	0.01**	ns	0.01**	0.01**	ns
		Contrast positions 0.7 m above and 4 m below source area						
B-FS vs. FS	1	ns	0.02*	ns	ns	ns	0.04*	ns
		Contrast positions 4 m above and 8 m below source area						
B-FS vs. FS	1	ns	ns	0.04*	ns	ns	ns	ns

* Significant at the 0.05 probability level.
** Significant at the 0.01 probability level.

pended and transported in runoff with little deposition below barriers (Dabney et al., 1995).

The ANOVA in Table 2 shows that the B-FS treatment reduced erosion more than the FS at 0.7 ($P < 0.01$) and 4 m ($P < 0.05$), but differences in sediment reduction between the treatments at 8 m were not significant. Sediment reduction at 8 m was 99% for the B-FS and 96% for the FS treatment. We conjecture that the relatively gradual decrease of sediment mass vs. distance for the FS, in contrast to that in B-FS, is due to little ponding resulting in more transport of sediment past the source area boundary and then sequential deposition of first coarser and subsequently finer sediments with distance. Other studies also have reported a gradual decrease of sediment with distance in fescue FS (Chaubey et al., 1994; Daniels and Gilliam, 1996).

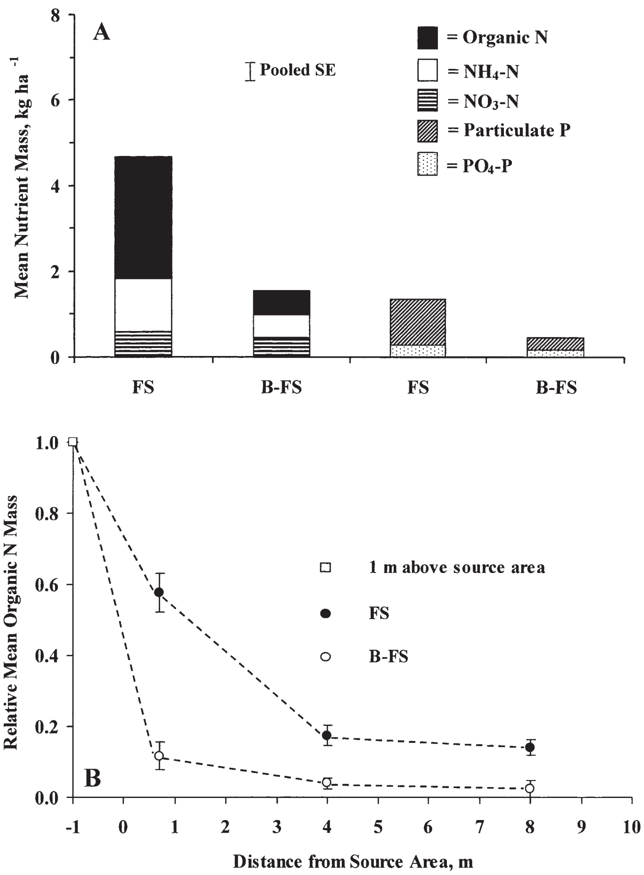

Fig. 4. Comparison of (A) mean organic N, particulate P, NH_4–N, NO_3–N, and PO_4–P exiting the 0.7 m of fescue filter strips with barriers (B-FS) and fescue filter strips without barriers (FS); and (B) relative organic N with distance of fescue filter strips with barriers (B-FS) and fescue filter strips without barriers (FS). Error bars are standard errors of the mean (n = 3).

These results show that barriers above FS can improve the conservation performance of FS to control soil loss under concentrated flow. Barriers with FS may help prevent head-cut formation in ephemeral rills by allowing sediment deposition upslope of the B-FS. Barriers planted across swales and above ephemeral gully heads would help stop the development of concentrated flow by retarding runoff and trapping sediment; thus, barriers can promote a favorable environment for revegetation in these areas.

Nitrogen and Phosphorus

Mean nutrient mass in runoff at the 0.7 m distance below the B-FS and the FS is presented in Fig. 4A. The ANOVA in Table 2 shows that differences between B-FS vs. FS were significant for organic N, particulate P, and NH_4–N ($P < 0.01$), but not for NO_3–N and PO_4–P. The B-FS trapped 4.9 times more organic N, 2.3 times more NH_4–N, and 3.7 times more particulate P than FS. The greater trapping of organic N and particulate P in B-FS is most likely due to sediment deposition above the B-FS. Reduction of organic N and particulate P was significantly correlated ($r^2 = 0.92$; $P < 0.01$) with sediment. The greater NH_4–N retention in B-FS is most likely due to adsorption by sediment particles settling upslope from the B-FS. Increased infiltration above the B-FS is most likely another mechanism for NH_4–N reduction. A study on a Coland silty clay loam (fine-loamy, mixed, superactive, mesic Cumulic Endoaquoll) found that 1-h cumulative infiltration under switchgrass was five times higher than that in row crop and pasture (Bharati et al., 2002). Delay in runoff above B-FS likely enhances infiltration, promoting deposition of PO_4–P.

Nitrogen and Phosphorus Transport vs. Filter Strip Length

Nutrient transport was also reduced with distance for both treatments as with sediment (Fig. 4B, 5A, 5B, 6A, and 6B). Figures 4B and 6B show that B-FS and FS reduced nutrient transport with distance, but the ANOVA in Table 2 indicates that differences between B-FS and FS at the 8-m position were not significant. Most nutrients were trapped in the upper 0.7-m strip in both treat-

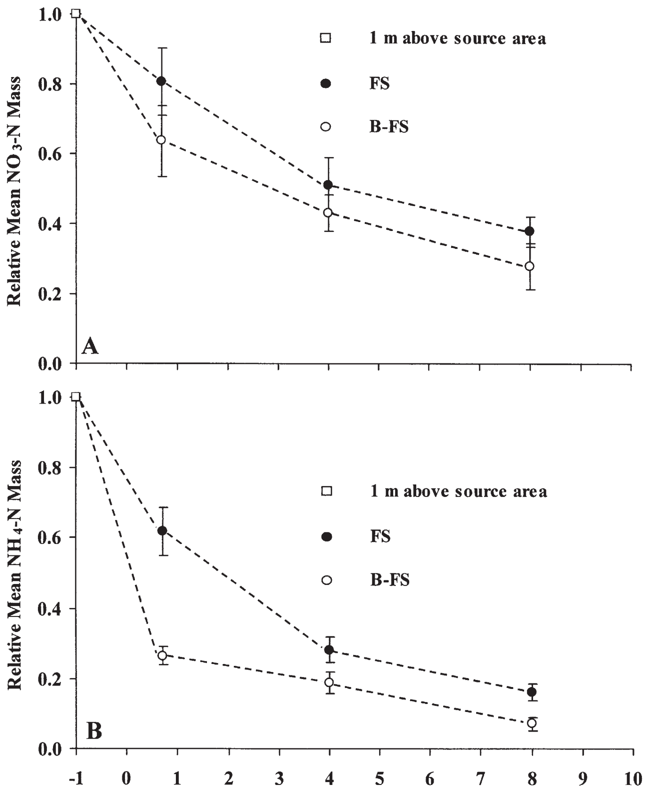

Fig. 5. Length effect of fescue filter strips with barriers (B-FS) and fescue filter strips without barriers (FS) on relative (A) particulate P and (B) PO_4–P mass. Error bars are standard errors of the mean (n = 3).

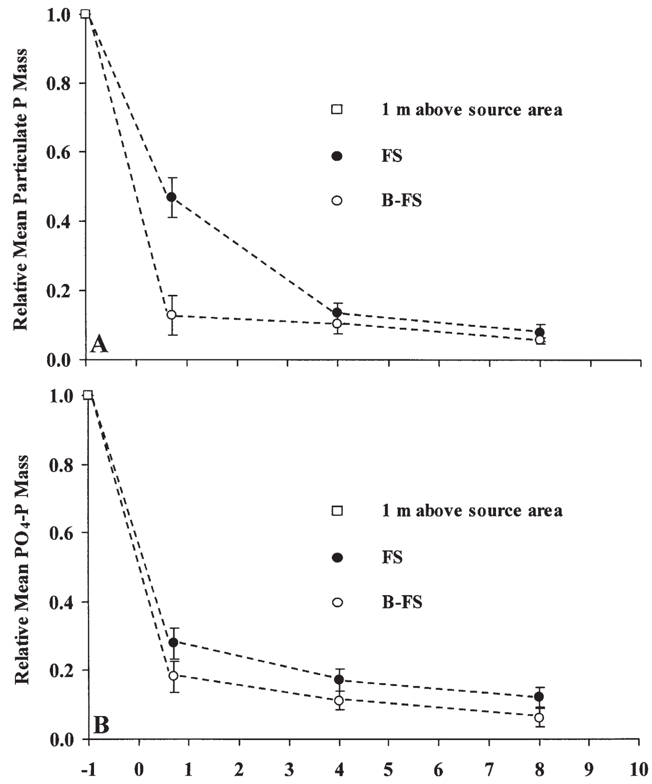

Fig. 6. Length effect of fescue filter strips with barriers (B-FS) and fescue filter strips without barriers (FS) on relative (A) NO_3–N and (B) NH_4–N mass. Error bars are standard errors of the mean (n = 3).

ments where B-FS retained an average of 87% for organic N and particulate P and an average of 78% for NH_4–N and PO_4–P. The FS reduced an average of 48% for organic N and particulate P, 38% of NH_4–N, and 71% of PO_4–P. The B-FS reduced NO_3–N 39% and FS reduced 19%. The lower NO_3–N reduction may be because it is not adsorbed by sediment. This is supported by results from a study reporting that barriers and fescue FS removed NO_3–N less than total N and P on a Sharpsburg silty clay loam (fine, smectitic, mesic Typic Argiudoll) (Schmitt et al., 1999). Organic N and particulate P were likely deposited with sediments (Barfield et al., 1998). Reduction of NH_4–N and PO_4–P is due to adsorption by barriers, fescue, and sediment. Phosphates react readily with clay particles and precipitate with sediment (Abu-Zreig et al., 2003).

The 8-m B-FS reduced 98% of organic N, 93% of NH_4–N, 73% of NO_3–N, and an average of 94% of particulate P and PO_4–P. In contrast, the 8-m FS reduced 86% of organic N, 84% of NH_4–N, 63% of NO_3–N, 92% of particulate P, and 87% of PO_4–P. The reduction of N and P in the B-FS treatment in this study is greater than that reported by Eghball et al. (2000), who found that 0.75-m barriers reduced 27% of total N, 52% of NH_4–N, 38% of particulate P, and 56% of PO_4–P on a Monona silt loam (fine-silty, mixed, superactive, mesic Typic Hapludoll) at 12% slope. Their steeper slope (compared with our 5%) probably reduced the barrier effectiveness.

Runoff from Source Areas with Additional Inflow

Mean runoff depth by pollutant source area size is shown in Fig. 7A. Depth of runoff increased linearly ($r^2 = 0.99$) with added runoff water at all sampling points as expected. Runoff depth 1 m above the source area boundary was the greatest because of the relatively low infiltration rates for bare soils with high antecedent moisture (Bharati et al., 2002). The ANCOVA at 0.7 m in Fig. 7A showed that the variance was not significantly different between treatments. Moreover, treatment regression slopes were not different ($P > 0.10$); but they had significantly different intercepts ($P < 0.05$), indicating that B-FS was more effective than FS for all inflow rates. The B-FS reduced an average of 10% more runoff than FS. Results indicate that barriers in B-FS significantly reduced concentrated runoff more than an equal length of FS under supplemental runoff water.

Erosion from Source Areas with Additional Inflow

Mean sediment mass data by distance and pollutant source area (inflow rate) are presented in Fig. 7B. Sediment vs. pollutant source area at the source area boundary had a significant quadratic response ($P < 0.01$) with increasing erosion at high runoff rates ($r^2 = 0.98$). Source area sediment ranged from 1.9 Mg ha^{-1} for a 1×-sized source area to 11 Mg ha^{-1} for 2×-sized source area. Sedi-

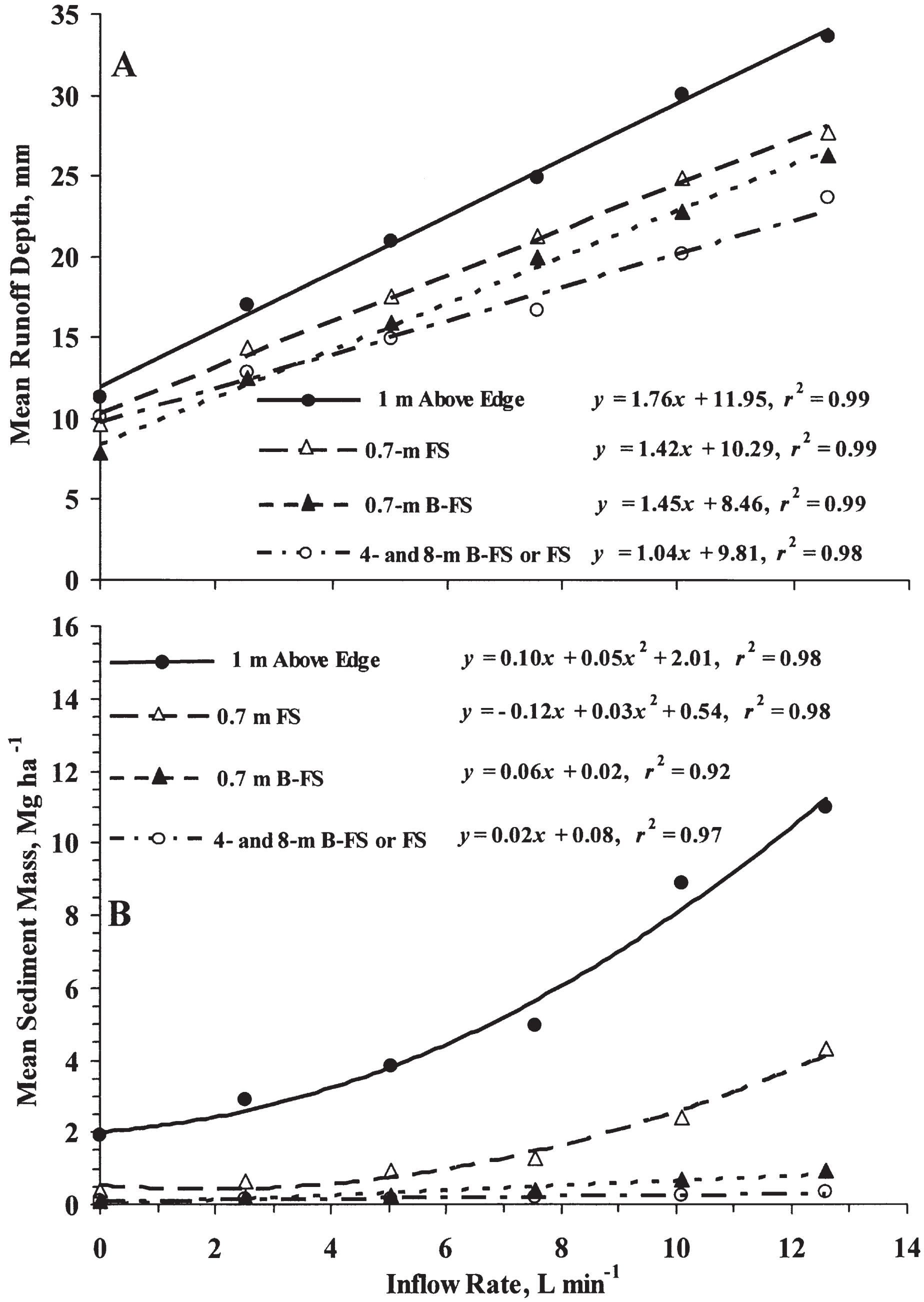

Fig. 7. Relationship of mean (A) runoff depth and (B) sediment mass with simulated inflow rates by distance at 1 m above the downslope edge of the pollutant source and at 0.7, 4, and 8 m within the fescue filter strips with barriers (B-FS) and fescue filter strips without barriers (FS).

ment leaving the 0.7-m FS was higher than in B-FS and increased quadratically with runoff ($r^2 = 0.99$; Fig. 7B). For a 1×-sized source area, B-FS trapped 90% of the sediment while FS trapped 72%. Effectiveness of the FS treatment for reducing sediment loss decreased with additional inflow rates. This was not the case for the B-FS, which did not change significantly with inflow rates ($r^2 = 0.92$; $P < 0.01$; Fig. 7B). The effectiveness of FS decreased from 72 to 60% when source area size increased from 1× to 2×. The relative sediment mass in Fig. 8 shows that B-FS was more effective than FS for reducing sediment at 0.7 m. The B-FS was more effective than FS in reducing sediment for all source area sizes at 0.7 m ($P < 0.01$). These results agree with Dillaha et al. (1989), who found that the fescue FS effectiveness decreased by 39% in 1.5 h of rainfall simulations at 50 mm h^{-1}. Magette et al. (1989) also reported that the ability of fescue FS to trap sediments decreased with increased runoff rates on a Woodstown sandy loam. Sediment reduction at 4 and 8 m for both treatments was nearly constant with inflow rate ($r^2 = 0.97$; $P < 0.01$).

Ponding above the B-FS was greater than found in our previous study without supplemental runoff. The ponded area extended 0.94 ± 0.05 m upslope of the B-FS with a depth of 0.17 ± 0.03 m. In contrast, runoff ponding for the FS treatment was negligible. The upper 0.3 m ± 0.05 of FS was overtopped with sediment particularly at source areas > 1.6×. The FS fescue grass bent

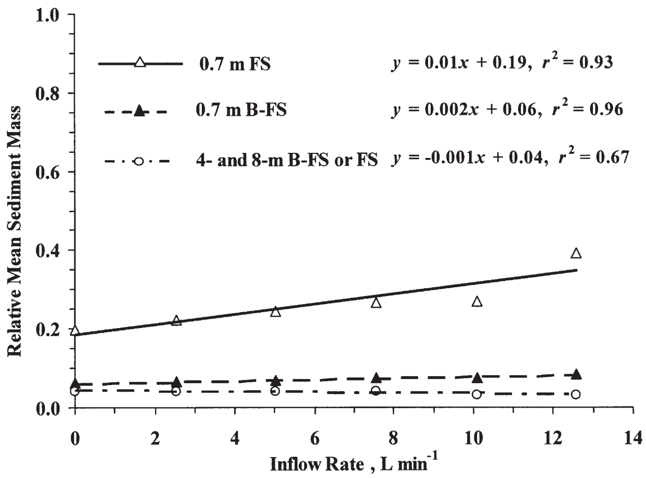

Fig. 8. Relative sediment mass by inflow rate of fescue filter strips with barriers (B-FS) and fescue filter strips without barriers (FS).

because of sediment load in contrast with switchgrass barriers, which remained upright throughout the simulations. Indeed, Dunn and Dabney (1996) reported that the modulus of elasticity of switchgrass was four times higher, and the strength was three times higher than for fescue, implying that switchgrass would offer higher resistance to runoff before being bent over as compared with FS.

Sediment deposition was evident in the ponded area of B-FS, which developed a sediment delta with a depth of 0.13 $\pm$ 0.03 m at 12.5 L min^{-1} of additional inflow. Abu-Zreig et al. (2003) stated that the sediment accumulation causes a significant reduction of the fescue FS for reducing sediment transport with time. Results from a watershed-scale study also showed that concentrated flow from large rainfall events ($>$50 mm h^{-1}) overwhelmed the FS below cultivated fields, making them ineffective on a Cecil sandy loam (fine, kaolinitic, thermic Typic Kanhapludult) and Georgeville silt loam (fine, kaolinitic, thermic Typic Kanhapludult) (Daniels and Gilliam, 1996). Bending of grass in the FS created conditions for channelized flow development. Concentrated runoff flowed through only 60% of the FS width in the upper 0.4 m while increasing sediment transport and decreasing sedimentation.

The increased effectiveness of B-FS in spring when runoff and erosion rates are often highest has important implications. In Missouri, between 50 and 70% of runoff occurs from March to May (Zhu et al., 1989; Ghidey and Alberts, 1998). This is also the time when most of the transport of chemicals by runoff occurs (Alberts et al., 1993; Donald et al., 1998). Our study results show that barriers in conjunction with fescue FS can better reduce sediment losses in runoff compared with FS alone under concentrated inflow conditions and where FS are $<$8 m wide. Results also show that B-FS may be effective in reducing dissolved nutrients in runoff and sediment-bound chemicals leading to reduction of NPS pollutants.

While barriers in the B-FS treatment were highly effective in reducing soil and nutrient loss in concentrated flow within the context of this study, they may be less effective on steeper slopes and higher sediment transport under concentrated runoff. This study did not assess the failure threshold of barriers. The B-FS also may be less effective where runoff concentrates and sediment accumulates from large source areas. A survey of demonstration sites of grass barriers showed that barrier effectiveness for reducing concentrated flow depends on site topography (sites established in the Long Branch Watershed with the cooperation of private landowners in northern Missouri; P. Los, 2003, personal communication). Barrier performance on steeply sloping fields in this watershed was questionable. Thus, some caution should be exercised when transferring the results of this study to sites differing in topography and source-area size. The actual effectiveness of B-FS and FS for reducing concentrated flow induced soil and nutrient loss in this study may not be perfectly related to actual field conditions. This is because the inflow erosivity and nutrient concentration were not at field equilibrium values, since inflow without sediment or nutrients was added at the upper plot borders to simulate conditions from larger runoff areas.

CONCLUSIONS

Results from this study show that narrow switchgrass barriers above a fescue FS are more effective than the FS alone for reducing runoff sediment transport and some nutrients from concentrated field runoff flow. Dormant barriers are as effective as active barriers for reducing runoff ($>$10%) and sediment ($>$90%) and perform better than FS for equal length of 0.7 m. The FS effectiveness decreases rapidly with supplemental runoff while barriers, even when dormant, remain rigid, ponding runoff. Results also show that sediment reduction increases with distance of B-FS and FS, but $>$60% of sediments is retained by the 0.7 m of B-FS and FS below the source area. Barriers promote deposition of nutrients bound to sediment by ponding runoff and possibly enhancing infiltration in contrast with FS that offered reduced resistance to concentrated flow. Our results suggest that both active and dormant switchgrass barriers, when used in combination with fescue FS, can improve the conservation effectiveness, and they may be a practical and economical alternative or supplement to conservation structures for reducing soil and nutrient loss in concentrated flow.

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